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Thermal Study for a Cylindrical Liquid-Fuel Oven for Melting Plastic Waste

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ABSTRACT

The aim of this study is to verify the energy performance of a furnace using used motor oil as fuel, enabling temperatures of up to 400°C to be reached. The heat balance, the subject of this study, is obtained by determining the quasi-static heat transfers during the cooking of waste plastics. An efficiency of around 92% is achieved, with most of the combustion energy being carried away in the flue gases and the rest stored in the furnace walls and openings. To reduce these losses, the furnace's energy efficiency must be optimized by controlling the temperature of the combustion air and fumes.

Keywords: Rotary furnace, plastic waste, engine oils, combustion, energy efficiency.

INTRODUCTION

From technical point of view, a furnace is a production tool designed to produce or transform materials by means of heat transfer between a heat source and the material to be processed [1]. In particular, ceramic furnace are masonry structures designed to bring a material (clay bricks, tiles, ceramic cores, etc.) to very high temperatures to affect a physical or chemical transformation [2]. They are considered to be very thermally inefficient systems, as the amount of heat used to heat the parts themselves is low [3]. Most of the heat used to heat the furnace escapes through the openings or the chimney in the form of losses [4]. In the context of Sahelian countries, the persistent use of charcoal and oil as fuel in these furnaces is a scourge from the point of view of deforestation of the plant cover, but non-renewable fossil fuels are also scarce and expensive [4]. As a result, optimizing the furnace by substituting used motor oil for fossil fuels represents a major economic challenge, since it would both exploit a widely available resource and provide a new impetus for the industrial sector.

The aim of this work is to recover used motor oils for reuse as a new source of exploitable heat energy, while limiting thermal losses from the furnace in order to achieve optimum efficiency. The studied furnace consists of three parts: the combustion chamber, the melting tank and the chimney. We will first present the furnace design model and operating mode, followed by the heat balance of the operation, then the results, discussion and outlook.

MATERIALS & METHODS

Materials

1.-Presentation of the furnace

The experimental device studied is a furnace running on recycled motor oil. It consists of, of a cylindrical enclosure with a capacity of 1.4 m^3 (figure 1) built of masonry using local materials (stainless steel, refractory bricks, rock wool etc). The construction is made of stainless-steel sheets and lined with refractory bricks. Rockwool was used to insulate the oven and door. Energy supply is guaranteed by burners placed inside the combustion chamber.

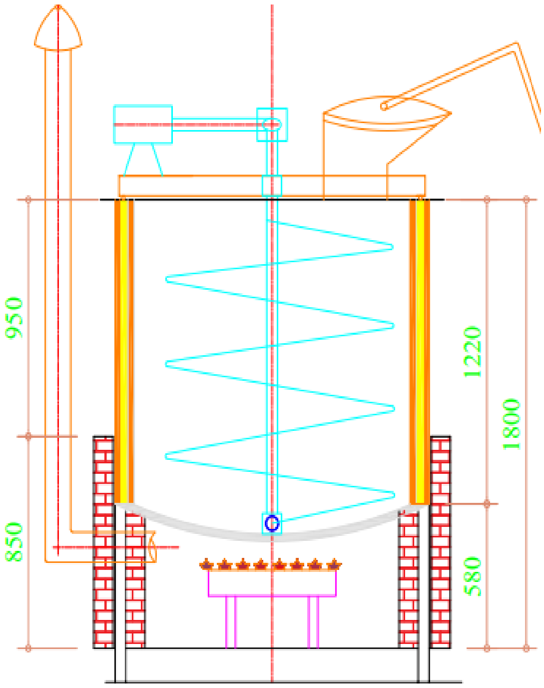

Figure 1: Waste plastic incinerator oven

2.-Mode of operation

The oven can be likened to a heat exchanger between the charge (plastic waste), which occupies almost all the space inside the oven, and the gas. The charge is baked in three phases: The first, called pre-heating phase, in which the product is heated from ambient temperature to a high temperature of around 200°C. The second is the firing phase, where the temperature varies between 200°C and 400°C. Finally, there's the cooling phase, during which the temperature of the charge gradually drops. In fact, the heat supplied to the charge comes solely from the heat supplied by burners in the form of flames.

3.- Thermal balance

The efficiency of a furnace is the ratio of the useful energy Q_u to the energy Q_T that must be supplied to the furnace in the form of fuel or electricity. Calling Q_p the various heat losses, we derive

$$\eta = \frac{Q_u}{Q_T} \quad \text{avec} \quad Q_u = Q_T - Q_p \qquad (1)$$

Energy provided by fuel Q_T : This is the total amount of energy supplied by the burners, where the heat supplied by natural gas combustion is given by the product of the hourly flow rate (D) of natural gas and its lower calorific value (LCV).

$$Q_T = \mathrm{D} * \mathrm{PCI} \qquad (2)$$

Heat loss from walls Q_P : These losses occur mainly by convection against the inner wall, then are transmitted by conduction to the outer wall, and finally by convection into the surrounding environment. In particular, taking the furnace as a hollow cylinder with outer radius Re and inner radius Ri, conduction is expressed by the classical relationship.

$$Q_P = \int_0^t \varphi\, dt = \frac{2\pi\lambda L}{\ln\left(\frac{R_{ext}}{R_{int}}\right)} \int_0^t (T_e - T_i)\, dt \qquad (3)$$

The transfer of energy from the inside interface to the outside of the furnace is expressed by the following equations:

$$Q_p = \frac{T_i - T_e}{\frac{\ln\left(\frac{R_{ext1}}{R_{int1}}\right)}{2\pi\lambda_{steel1} L} + \frac{\ln\left(\frac{R_{ext2}}{R_{int2}}\right)}{2\pi\lambda_{isolate} L} + \frac{\ln\left(\frac{R_{ext3}}{R_{int3}}\right)}{2\pi\lambda_{steel2} L} + \frac{1}{hS}} \qquad (4)$$

hc: Convection coefficient of the hot fluid;
ƛ: Thermal conductivity of air (w/m. K);
h: Convection coefficient of cold fluid;
R

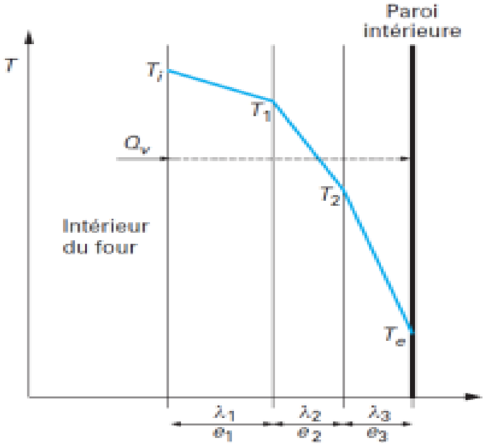

Figure 2: Temperature evolution in a composite wall with three layers of refractory and insulating materials [5].

Losses through oven openings Q_e: The quenching furnace contains several openings, each with a specific role (product entry and exit, inspection door, etc.). These openings promote heat transfer from inside to outside the furnace, by convection and, above all, by radiation.

$$Q_e = KS\Delta T \quad \text{avec} \quad K = \frac{1}{\frac{1}{h_c}+\frac{e}{\lambda}+\frac{1}{h_f}} \qquad (6)$$

hc: Convection coefficient of the hot fluid;
ƛ: Thermal conductivity of air (w/m. K);
hf: Convection coefficient of cold fluid;
e: Thickness of cover (in meters)

Heat loss from chimney Q_f : The heat lost through the flue gas is the product of the average flue gas volume, the flue gas temperature and the specific heat of the flue gas (at outlet temperature).

$$Q_f = V_{mf} * T_f * C_{pf} \qquad (7)$$

T_f: Fumes temperature at furnace outlet;
C_{pf}: Specific heat of flue gas at outlet temperature.
Vmf: Average volume of furnace fumes

Energy lost through combustion products: To be able to evaluate the furnace, the flow of air and fuel into the combustion chamber must be known. Air and fuel are mixed at the burners, and burned in the combustion chamber [5]. The combustion chamber consists of tubes placed around the perimeter of the furnace. Combustion occurs with an excess of air, and is typical of all hydrocarbons: one carbon atom requires one oxygen molecule, and one hydrogen atom requires 0.25 oxygen molecules [6].

This method involves replacing the fuel gas used in a furnace with an equivalent fuel of molecule $C_m\,H_n$. The stoichiometric quantity of air required to burn a hydrocarbon mixture is determined by the combustion reaction [7]:

$$C_m\,H_n + \left(m + \frac{n}{4}\right) O_2 \longrightarrow mCO_2 \cdot \frac{n}{2} H_2O \qquad (8)$$

Theoretical air and excess coefficient: The oxidizer used in combustion is generally air rather than pure oxygen. The composition of air is approximately, in molar fractions, 21% dioxygen and 79% nitrogen [8]. The latter is considered an inert element in combustion. If we consider a hydrocarbon, its combustion reaction with air is written as follows [9]:

$$C_m\,H_n + \left(m + \frac{n}{4}\right) O_2 + \left(\frac{79}{21}\right)\left(m + \frac{n}{4}\right) N_2 \longrightarrow mCO_2 + \frac{n}{2} H_2O + \left(\frac{79}{21}\right)\left(m + \frac{n}{4}\right) N_2 \qquad (9)$$

The ratio of air and fumes volume to fuel volume are deduced from the combustion reaction as follows [10]:

$$\frac{V_{air}}{V_{fuel}} = \frac{m+\frac{n}{4}}{0{,}21} \qquad (10)$$

$$\frac{V_{fumes}}{V_{fuel}} = \left(\frac{79}{21}\right)\left(m + \frac{n}{4}\right) + m + \frac{n}{2} = 4{,}762m + 1{,}44n \qquad (11)$$

However, combustion is never achieved with the stoichiometric amounts of air. For complete combustion, the heating system should be operated with 2 to 4% excess oxygen [11]. The amount of air in a heater operating with excess O_2 will come according to the following equation:

$$\frac{V_{air}}{V_{fuel}} = \frac{m + \frac{n}{4}}{0{,}21} + \left(\frac{4{,}762m + 1{,}44n}{1 - \frac{\%O_2}{21}}\right) * \frac{\%O_2}{21} \qquad (12)$$

$$\%\, excess\ air = \frac{(4{,}762m + 1{,}44n) * \%O_2}{(1 - \frac{\%O_2}{21})(m + 0{,}25n)} \qquad (13)$$

Thermal efficiency: Thermal efficiency is defined as the ratio between the heat absorbed in the furnace and the heat released by combustion [12]. For good thermal efficiency, the flue gas temperature should be between 120 and 200°C.The variables that reduce furnace efficiency are: The presence of excess air and heat loss through the walls [13].

Heating operating efficiency is expressed as follows [14]:

$$\eta = 100 - Q_{parois} - \frac{Q_{fumes}}{\text{Enthalpy of combustion+heat air}} \quad (14)$$

The enthalpy of combustion is taken at 15°C

$$\eta = 100 - Q_{par} - \frac{\frac{V_{fm}}{V_{fu}} C_{P\,fm} t_{fm-15} \rho_{fm}}{\text{PCI}+\frac{V_{air}}{V_{fuel}} C_{P\,air} t_{air-15} \rho_{air}} \quad (15)$$

with

η = energy efficiency

$\mathbf{Q_{par}}$ = Energy lost through walls

$\mathbf{C_{pfm}}$ = heat capacity of fumes

$\mathbf{V_{fm}}$ = Volume of fumes

$\mathbf{V_{fu}}$ = Volume of fuel

RESULTS AND DISCUSSION

The results of the heat balance calculation are shown in Table

Table 1: Oven heat balance

Energy	Values in (W)
Walls Q_p	155.62
Opening Q_e	6.8
Chimney Q_c	316 214
Ceiling Q_c	43.72
Combustible	3 841 808

Calculations give a satisfactory combustion efficiency η of around 92%.

Efficiency is therefore acceptable. We note, however, that losses in the chimney are higher. Thermal efficiency depends on all losses, but particularly those caused by flue gases.

the figure below shows the evolution of the percentage of excess air as a function of excess oxygen.

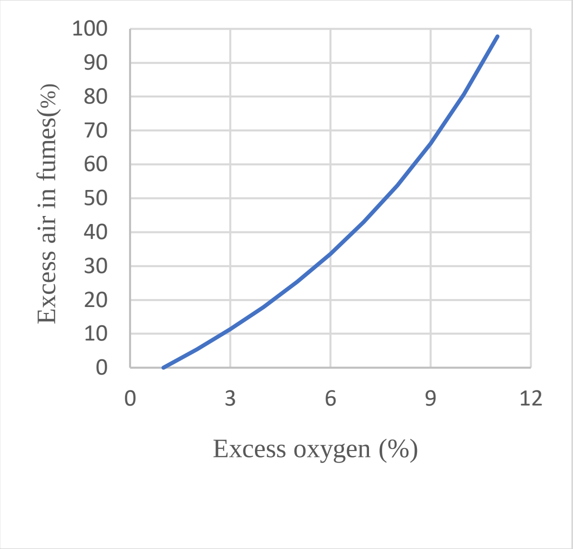

Figure 3: Excess air as a function of excess oxygen

We can see that the excess air in the fumes increases proportionally with the increase in oxygen in the air, from 0 to 9%.

From a 9% of oxygen in the air, the evolution of excess air in the fumes increases much more rapidly

The following three-dimensional graph shows the influence of air preheating and flue gas temperature on furnace thermal efficiency.

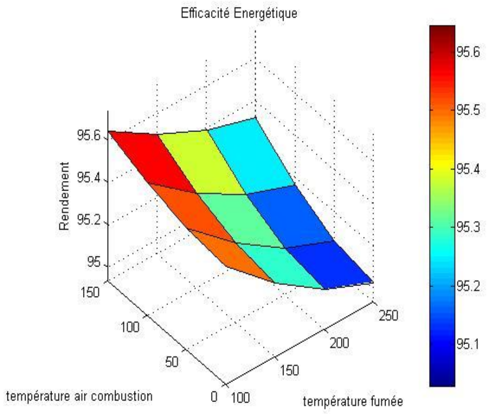

Figure 4: Thermal efficiency as a function of air and flue gas temperatures

We note that air preheating considerably increases furnace efficiency, while the rise in flue gas temperature increases chimney losses, which is a poor sign of furnace operation, leading to a reduction in energy efficiency.

The figure 5 below shows the evolution of the oven's interior temperature as a function of the plastic loading height.

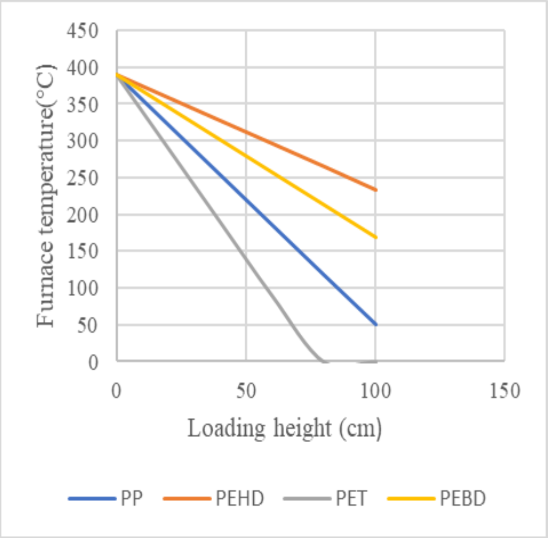

Figure 5: Oven temperature variation as a function of plastics loading height

Figure 5 shows that the temperature of the plastic decreases as a function of the loading height for all types of plastic. The temperature drop is much greater for polyethylene terephthalates (PETE) and polypropylene (PP), which have lower thermal conductivities.

On the other hand, for high- and low-density polyethylene (HDPE and LDPE), the temperature drop is less significant, so these polymers have higher thermal conductivities.

CONCLUSION

The proposed model has enabled us to characterize the temperature rise, which will contribute to a better programming of the firing of various types of plastic waste according to an optimal curve determined experimentally. We also verified the thermal efficiency of the furnace, as well as the different types of heat loss. Our calculations showed that the greatest losses are to be found in the chimney, which can considerably reduce the furnace's efficiency. To optimize furnace operation and profitability, we propose to install an air preheating system. This will increase furnace efficiency and reduce losses due to excess air.

Declaration by Authors

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Conflict of Interest: The authors declare no conflict of interest.

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